Wild cables and survivability of macroscopic molecular structures in hot tokamak plasmas

A.B. Kukushkin, V.A. Rantsev-Kartinov

INF RRC "Kurchatov Institute", Moscow, 123182, Russia
kuka@qq.nfi.kiae.su, rank@qq.nfi.kiae.su

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The evidences for tubular rigid-body structures are found in tokamak plasmas, which are similar to long-living filaments observed in a Z-pinch ([1] Kukushkin, Rantsev-Kartinov, Proc. 26-th EPS conf., http://epsppd.epfl.ch/cross/p2087.htm). These structures are suggested to be a "wild cables" produced by the channelling of EM energy pumped from the external electric circuit and propagated to the plasma core in the form of the high frequency EM waves along hypothetical (carbon) microsolid skeletons [1] which are assembled during electric breakdown. It is shown that such skeletons may be protected from the high-temperature ambient plasma by the TEM waves produced thanks to the presence of microsolid skeletons.

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1. Introduction.

Recently the anomalously high survivability of some filaments in laboratory plasmas was illustrated [1(a)] with tracing the history of the typical long rectilinear rigid-body block in a Z-pinch. The pictures were taken in visible light at different time moments from different positions, during about half a microsecond, that is comparable with the entire duration of the Z-pinch discharge (see Fig. 1 in [1(a)]). The original images were processed with the help of the method [2(a,b)] of multilevel dynamical contrasting (MDC) of the images.

The phenomenon of long-living filaments (LLFs) [1,2] in various laboratory plasmas (gaseous Z-pinches [2(a,c)), plasma foci [2(e)], and tokamaks [2(d)]) has lead us to a conclusion [1(a)] (see also references therein) that only the quantum (molecular) long-range bonds inside LLFs may be responsible for their observed survivability, rather than the mechanisms of a classical particles plasma. Specifically, the carbon nanotubes have been proposed to be the major microscopic building blocks of the respective microsolid component of LLFs because such nanotubes may be produced in various electric discharges (see, e.g., [3]).

2. Rigid-body structures in tokamak plasmas.

An analysis of available databases carried out with the help of the MDC method [2(a,b)], shows the presence of tubular structures. The typical examples for tokamaks TM-2, T-4, T-6 and T-10 (major radius $R = 0.4$, 0.9, 0.7, 1.5 m, minor radius $a = 8$, 20, 20, 33 cm, toroidal field $B_T = 2$, 4.5, 0.9, 3 T, total current $I_p \sim$ 25, 200, 100, 300 kA, electron temperature $T_e(0) \sim 0.6$, 3, 0.4, 2 keV, electron density $n_e(0) \sim (2, 3, 2, 3) \times 10^{13} cm^{-3}$, respectively) are given in [4]. The figures presented there are taken in visible light with the help of a strick camera and high-

speed camera. The effective time exposure is about 10 μsec. The major features of the structuring are as follows:

(a) the length scale of the rigid-body tubular structuring varies in a broad range, from comparable with the minor radius of a tokamak to less than millimeter scale;

(b) the typical tubule seems to be a cage assembled from the (much) thinner, long rectilinear rigid-body structures which look like a solid thin-walled cylinders;

(c) the (almost rectilinear) tubules form a network which starts at the farthest periphery and is assembled by the tubules of various directions;

(d) a radial sectioning of the above network is resolved which looks like a distinct heterogeneity at a certain magnetic flux surface(s) (such a sectioning was suggested [1(b),2(d)] to cause the observed internal transport barriers in tokamaks).

The pictures include, in particular, the periphery of the tokamak T-10 plasma illuminated by the carbon pellet emission (the pellet track is outside the picture). The system of concentric circles and the inner almost rectilinear tubule located approximately on the axis of these circles form together a sort of the squirrel's wheel. Major axis of this system is directed nearly orthogonal to toroidal magnetic field. The system is 5 cm long and of $4 \div 4.5$ cm diameter. The central and boundary vertical tubules are of 4 mm diameter. Similar structures appear to form in all tokamaks, i.e. with no regard to pellet injection.

3. Probable mechanism of formation and survivability of microsolid skeletons in tokamak plasmas.

(i) A deposit of carbon nanotubes, of the relevant quantity, is produced at the inner surface of the chamber during discharge training, from either graphite-containing construction elements (like, e.g. limiters or walls) or carbon films produced by the deposition of the organic oils normally used in the vacuum pumping systems (the nanotubes may form due to rolling up of monolayers ablated from solid surfaces or thin films).

(ii) Electrical breakdown occurs along chamber's surface (or its part, namely, the inner side of the torus) and is based on the substantially enhanced rate of (cold) autoemission and thermoelectric emission of electrons by the nanotube (as compared to macroscopic needles).

(iii) The microsolid skeletons are assembled from individual nanotubes which are attracted and welded to each other by the passing electric current to produce self-similar tubules [1(a)] of macroscopic size, of centimeter length scale and larger (this electric current is produced by the poloidal magnetic field B_{pol} pumped from the external circuit into the chamber).

(iv) Once the skeleton (or its relevant portion) is assembled, the substantial part of the incoming B_{pol} brakes at it and produces a cold heterogeneous electric current sheath made of conventional plasma. A part of B_{pol} near the skeleton is bouncing along its every rectilinear section (i.e. between the closest points of the deviation, even small enough, from rectilinearity). This produces a high-frequency EM wave which, in turn, produces, by the force of the high-frequency (HF) pressure [5] (sometimes called in literature the Miller force), the cylindrical cavities of a

depleted electron density (primary channels) around the skeletons.

(v) At the skeleton's (and plasma column) edge the bouncing boundary of the cavity from the scrape-off layer side produces a HF valve for the incoming B_{pol}, because of the node of the standing wave at the edge. This works as a HF convertor of a part of the incoming B_{pol} which is transported then along the skeleton in the form of EM waves. (Besides, a part of B_{pol} which reaches the cavity in the conventional regime of the diffusion of B_{pol}, is transformed into a HF field by the oscillating boundary of the cavity). The EM waves sustain the cavity and protect the skeletons from direct access of thermal plasma particles. Therefore the skeleton appears to be an inner wire of the cable network (a *wild cable* network) in which the role of a screening conductor is played by the ambient plasma.

In this paper, we restrict ourselves to quantifying the above picture in its quasi-stationary stage of energy inflow through the wild cable network.

For the frequency ω_c of the major harmonic of EM oscillations trapped in radial direction in a cylindrical almost-vacuum cavity of effective radius r_c around microsolid tubule of length L_c, one has (ω_{pe} is plasma frequency, c, the speed of light):

$$\omega_c \simeq \pi c / L_c \leq \omega_{pe}. \tag{1}$$

For tokamak geometry, one has the following chain of transformations of EM waves. The cavities at plasma edge (they normally possess some declination with respect to the boundary magnetic surface) allows the field lines of B_{pol} to move directly inside the cavity and thus produce the magnetic (H) wave. For the strongest EM wave among H waves, H_{11} wave, one has: $\lambda \simeq 2L_c \geq \lambda_{crit} \sim \alpha r_c$, where λ_{crit} is the critical wavelength for free propagation of the respective EM wave in the cable ($\alpha_{H11} \approx \pi$). Therefore, the trapping of H_{11} wave in the edge cavity leads to the wiring of magnetic field lines round the inner wire that produces TEM and electric (E) waves propagating in both directions (the strongest wave among E-waves will be E_{01} wave). However, the E_{01} wave will also be trapped in the cavity ($\alpha_{E01} \approx 2.6$), in contrast to TEM wave ($\lambda_{crit}^{TEM} = \infty$). Also, the H and E-waves, in contrast to TEM wave, are detached from the wall (in radial direction, these waves are the standing ones) so that only the TEM wave can actually maintain the boundary of the cavity. Thus, the edge cable converts a part of B_{pol} into HF TEM wave propagating inward. The signs of this HF field of which a small part is reflected outward may be found in the measurements of EM fields outside plasma column (see below).

It is assumed also that the presence of an external stationary strong magnetic field doesn't influence substantially the form of the cavity, because even for $\omega_c \ll \omega_{He}$ (ω_{He} is electron gyrofrequency) the amplitude $\vec{E}_0$ of the HF electric field may have a non-zero component parallel to magnetic field (in that case we will assign $\vec{E}_0$ to the respective component of the amplitude).

The distribution of plasma density around the inner wire can be described by a set of equations for the two-temperature quasi-hydrodynamics of a plasma in a HF EM field [6]. Under condition $l_E \gg r_D$, where l_E is the characteristic length of spatial profile of $E_0(\vec{r})$ and r_D is Debye radius, one can neglect the deviation

from quasi-neutrality and arrive at quasi-Boltzmann distribution (see e.g. [6(b)]):
$n_e = n_{e0} \exp(-\Psi/(T_e + T_i))$, where $\Psi = e^2 E_0^2/(4 m_e \omega_c^2)$, n_{e0} is background density of plasma electrons. The condition for plasma detachment from the inner wire reads:

$$eU_0 \geq 2\pi(r_c/L_c)\sqrt{A m_e c^2 (T_e + T_i)}, \quad A \sim (r_w^2/r_c^2) \, ln(n_{e0}/n_{emin}), \qquad (2)$$

where U_0 is the effective voltage bias of the TEM wave in the cable ($E_0(r) \sim U_0/r$; r is the radial coordinate in a circular cylindrical cable, r_w, radius of inner wire), n_{emin} is the minimal density permitted, at a temperature T_e, for the inner wire to be not destroyed by the plasma impact. For tokamak case ($n_{e0} \sim 10^{13} cm^{-3}$), we take $A \sim 5$.

Equation (3) is to be coupled to the condition of the applicability of the concept of the $(-\nabla\Psi)$ force, $\rho \ll l_E$ (ρ is the amplitude of electron's oscillations in the HF electric field). For our estimates, this limitation, however, may be weakened and takes the form:

$$eU_0 \leq \pi^2 \, m_e c^2 \, r_c(r_c - r_w)/L_c^2, \qquad (3)$$

And finally, the HF electric field in the cables may be related to the observable turbulent electric fields because wild cables are the strong sources of electrostatic oscillations in plasma. As far as there should be a sort of the feedback between plasma and cavity, one may consider the cable's cavity as a soliton with such a strong reduction of the eigenfrequency (a redshift) that soliton's velocity becomes independent from dispersion. For $W/nT \leq 1$ ($W \equiv E_0^2/16\pi$) this gives rough estimate:

$$W/nT \sim (1 - (\omega_c/\omega_{pe})). \qquad (4)$$

At the quasi-stationary stage of discharge, one may evaluate the spatial distribution of the amplitude E_{turb} of the turbulent electric field, regardless of its spectral distribution, as being described, in radial direction with respect to the individual cable, by the scaling law of the TEM wave. For the contribution of a single cable, one has:

$$E_{turb}(r) \sim U_0/r. \qquad (5)$$

Equations (1), (2) and (3), along with rough estimates of Eqs.(4) and (5), establish a set of equations that enable one to evaluate the plausibility of the presence of wild cables in tokamak plasmas, using available data on measuring the values of ω_c [7] (and/or L_c) and E_{turb} [8].

Now we can test the problem for typical data from the periphery of the T-10 tokamak, keeping in mind the closeness of T-10 regimes analyzed in [7,8] and those for Figure 4. First, the spectra of the HF EM field in the gap between the plasma column and the chamber measured in the GHz frequency range revealed [7] a distinct bump at $\nu_c \sim (4 \div 5) \times 10^9 Hz$, of the width $\sim 2 \times 10^9 Hz$, which always exists in ohmic heating regimes and increases with electron cyclotron heating (this bump is a stable formation and it moves to the lower frequencies and turns into a peak only under condition of strong instabilities, especially disruption instability). This

gives $L_c \approx 3\ cm$. Note that this is in reasonable agreement with the data from the high-speed camera picture for T-10 plasma periphery where $L_c \approx 4 \div 5\ cm$.

Second, the analysis of observations of Stark broadening of deuterium spectral lines (and their polarization state) at the periphery of the T-10 tokamak in the region of $T_e \sim 100\ eV$, allowed [8] to estimate the spectral range of HF electric fields ($\omega \approx \omega_{pe} \sim 10^{11} Hz$), their amplitude ($E \sim 10 \div 20\ kV/cm$) and angular distribution.

For $L_c = 3\ cm, T_e = T_i = 100\ eV$, Eqs. (2) and (3) give a constraint $S \equiv (r_c - r_w)/L_c \geq 0.03$. For $(r_c - r_w) \sim r_c$, from Eq. (2), one can find the absolute minimum of voltage bias: $(U_0)_{min} \approx 5\ kV$. For $S = 0.03$, Eqs. (2) and (3) give $U_0 \approx 5\ kV$, while for $S = 0.1$ one has $15 \leq U_0\ (kV) \leq 50$. Further, Eq. (4) gives $E_0(r_c) \geq 50\ kV/cm$, while, for $r_c \sim 1 \div 2\ mm$ and $< r > \sim 1 \div 3\ cm$ ($< r >$ is the average distance between individual cables in the region of observation), Eq. (5) gives the estimate $E_0(r_c) \geq 10^2\ kV/cm$, or $U_0 \geq 10\ kV$. The results of numerical solution of the Poisson equation [6] show that, e.g., for $U_0 = 30\ kV$ at the distances $r \sim 2 \div 3\ mm$ the plasma density falls down, with respect to its background value, by the seven-eight orders of magnitude.

4. Conclusions

The experimental data of Sec. 2 and the model of Sec. 3 support the hypothesis [1] that plasmas with long-living filaments is such a form of the fourth state of matter, which is an intricate mixture of three other states (gaseous, liquid and solid). The presence of the inner wire (namely, electrically conducting microsolid skeleton) in the wild cable is responsible not only for the observed anomalous mechanical stability of this structure but also for the formation of TEM waves in the cavity that is critical for the self-sustainment of the cavity and for the transport of EM energy to plasma core.

It follows that observed structuring could be:

(i) a strong candidate for the nonlocal (non-difusion) component of heat transport (and observed phenomena of fast nonlocal responses) in tokamaks;

(ii) a powerful source of non-linear waves and (strong) turbulence throughout plasma volume;

(iii) a low-dissipation waveguide responsible for the spatial profile of poloidal magnetic field in tokamaks, rather than total resistance of plasma (in agreement with the observed applicability of Spitzer, or close, resistivity to describing the ohmic heat release in plasma);

(iv) a universal phenomenon in well-done laboratory plasmas and space; in particular, similar wild cables may form in gaseous and wire-array Z-pinches and be responsible for the fast nonlocal transport of EM energy toward Z-pinch axis.

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